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Thermal death kinetics and heating rate effects for fifth-instar *Cydia pomonella* (L.) (Lepidoptera: Tortricidae)

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Abstract

Thermal death kinetic parameters of fifth-instar codling moths (*Cydia pomonella* (L.)) and the effect of three heating rates (1°C min^{-1}, 10°C min^{-1}, and 18°C min^{-1}) on larval mortality were determined by a heating block system. The insects were heated to four temperatures (46°C, 48°C, 50°C, and 52°C) held for predetermined periods followed by 24 h storage at 4°C before mortality evaluation. Thermal death kinetics for fifth-instar codling moths followed a 0.5th order of kinetic reaction. Minimum time required to achieve 100% mortality of a given population decreased with temperature in a semi-logarithmic manner. No larval survival was observed in samples of 600 insects after exposure to 46°C, 48°C, 50°C, and 52°C for 50, 15, 5, and 2 min, respectively. Activation energy for thermal kill of fifth-instar codling moths at the heating rate of 18°C min^{-1} was estimated to be about 472 kJ mol^{-1}. The lethal time accumulated during the ramp period was about 1.8, 0.2, and 0.1 min for the heating rates of 1°C min^{-1}, 10°C min^{-1}, and 18°C min^{-1}, respectively. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Thermal death time; Kinetics; Heating block; Heating rate; Codling moth; Quarantine treatment

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1. Introduction

Interest in using heat treatments to provide quarantine security against pests in fresh and stored agricultural commodities has increased in the wake of regulatory actions over the use of pesticides. Concerns about pesticide effects on humans and the environment and implementation of the US Food Protection Act of 1996 will further limit use and availability of some widely used chemical fumigants, especially methyl bromide, against codling moth in fruits and nuts

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(UNEP, 1995). An understanding of intrinsic mortality parameters and relationships between applied heat and its cumulative effect on both pest and commodity is necessary for determining the suitability and effectiveness of an alternative heat treatment method.

Infesting pests differ very widely in tolerance to heat treatments. Thus, knowledge of the minimum required thermal energy to control infesting insects over a relatively large range of temperatures would provide flexibility for the design of suitable and effective thermal quarantine processes. Several researchers have reported heat resistance of codling moth instars (Yokoyama et al., 1991; Neven, 1994; Neven and Rehfield, 1995; Neven and Mitcham, 1996; Ikediala et al., 1999). Jang (1991) observed that much of the research on the application of heat treatments to obtain quarantine security has not been systematic. For example, different experimental and heat application methods have been used to assess the thermal resistance of codling moths, and reported information for codling moth or other insects is often confounded by the heat transfer phenomenon and the heat application method employed.

Heating rate is believed to have a significant effect on insect metabolism and physiological adjustment to the heat treatment (Evans, 1986; Neven, 1998a, b). Neven (1998a) reported that codling moth larvae might experience thermal conditioning and acclimation to the heat at heating rates between 0.13°C min^{-1} and 0.2°C min^{-1}. Consequently, a longer holding time is required at a final temperature in order to achieve the same mortality after a slower heating rate. For conventional heating, the heating rates in the interior of commodities ranged between 0.05°C min^{-1} and 2°C min^{-1}, depending on heating methods, type and size of commodity, and the end temperature (Wang et al., 2001b). In addition, the heating rate at the interior of a commodity decreases with time under a constant treatment condition due to decreasing temperature difference between the heating medium and the fruit. As a result, conventional heat treatments typically take long times to achieve required security against insects. Most insects may have adequate time to adapt to the heat and increase thermal resistance (Waddell et al., 2000).

Fast heating methods (10–20°C min^{-1} heat rates) based on radio frequency (RF) and microwave energy have been proposed to control insect pests in commodities to replace chemical fumigation (Nelson and Payne, 1982; Ikediala et al., 1999, 2001; Tang et al., 2000; Wang et al., 2001a). Recently, Ikediala et al. (2002) and Wang et al. (2001a) reported thermal treatment methods using 27 MHz RF energy to control codling moths in cherries and walnuts without significantly reducing product quality. Therefore, there is a need to study the effect of all possible heating rates on the thermal death kinetics of insects.

The objectives in this research were to study the thermal death time (TDT) kinetics of fifth-instar codling moths and to determine the effect of heating rates on mortality of this insect pest.

2. Materials and methods

2.1. Heating block system

A computer-controlled heating block system which provided heating rates from 0.1°C min^{-1} to 20°C min^{-1} was developed at Washington State University, Pullman, WA for studying thermal death kinetics of insect pests. Details of this heating system have been described in Ikediala et al. (2000) and the improved version in Wang et al. (2002). The death rate kinetics and the effect of heating rates on thermal mortality of insects were investigated using this heating system.

2.2. Heat treatment of codling moth larvae and mortality analyses

Fifth-instar codling moths, *Cydia pomonella* (L.), were used in experimental heat treatments. Yokoyama et al. (1991) showed this developmental stage to be the most heat tolerant. Codling moth larvae were obtained from the USDA-ARS Yakima Agricultural Research Laboratory, Wapato, WA. Before each heat treatment, 200 larvae were extracted from artificial diet (Toba and Howell, 1991) and placed in the heating block chamber. The system temperature was then ramped up at one of three heating rates (1°C min^{-1}, 10°C min^{-1}, and 18°C min^{-1}) to 46°C, 48°C, 50°C and 52°C. Insects were held at those final temperatures for three to five different periods that varied between 0.5 min at 52°C and 10 min at 46°C. These holding periods would allow a wide range of mortality levels including 100%. The heating rate of 1°C min^{-1} was selected to simulate the slow heating for fruits using conventional heat treatments such as forced hot air and hot water baths and the heating rates of 10°C min^{-1} and 18°C min^{-1} were used to simulate the fast heating for fruits using RF and microwave energies.

To compare the effect of heating rates on insect mortality, four temperature–time combinations, 46°C + 40 min, 48°C + 5 min, 50°C + 2 min, and 52°C + 1 min, were selected just below a complete kill level as described by the TDT curve (defining minimum temperature–time required to achieve 100% mortality in a given sample) developed at the heating rate of 18°C min^{-1}.

Control larvae were placed in the unheated block chamber for 50 min. For each temperature and holding time combination, including controls, 200 larvae were treated at a time and all treatments were repeated three times for a total of 600 larvae.

Commercial treatments would include rapid post-treatment cooling of cherries to minimize the effect on product quality, so the treated larvae were immediately moved to cold storage at 4°C and stored at this temperature for 1 day. After the cold storage, the larvae were held at 23°C, 60% RH in a 16:8 (L:D)h photoperiod for 1 day to minimize the effect of cold stupor before examination. Procedures for observing treated insects and calculating insect mortality were similar to those described in Wang et al. (2002).

2.3. Insect thermal kinetic modeling

Different methods have been used to analyze thermal resistance of insects. Probit analysis is the most common method. It is based on the assumption that the frequency of individual deaths in an insect population under constant temperature follows the standard normal distribution with cumulative probability of death increasing with time (Finney, 1971; Sokhansanj et al., 1990; Tang and Sokhansanj, 1993). The probit analysis neither gives the kinetic parameters for insect thermal mortality nor provides sufficient information from which new or other temperature–time combinations can be chosen. Thomas and Mangan (1997) critically reviewed several models for Mexican fruit flies. They recommended the use of a thermal dynamic kinetic model for estimating the efficacy of quarantine treatments in developing new treatment methods, but recommended use of the traditional probit analysis for confirming estimates. Jang (1986, 1991) detailed the advantages of the kinetic model for determining the thermal death rate parameters of fruit flies. Earlier, the use of probit 9 mortality as a criterion to ensure quarantine treatment security of fruits infested by fruit flies and other pests had been questioned by Landolt et al. (1984).

Several researchers have suggested that the logarithmic order of death was not always followed by microorganisms (Alderton and Snell, 1970; Moats, 1971; King et al., 1979). Jang (1986, 1991) used a modified logarithmic formula derived by Alderton and Snell (1970) to model thermal mortality of fruit flies. Thus, the knowledge of the fundamental kinetics for thermal death of insects allows the prediction of lethal times (LT) over a range of temperatures. Tang et al. (2000) described the TDT concept in detail and its applicability to model insect pest heat destruction kinetics. A significant advantage of the thermal kinetic model, whenever suitable to model death rates over the probit method, is the ability to predict the efficacy of a thermal process based on temperature–time history in host materials.

In developing a kinetic model to describe thermal kill of codling moth larvae, we used a classical kinetic model approach in which we determined the order of reaction and then determined the activation energy based on the dependence of reaction rate on temperature. In this analysis, the ratio change of insect survivals (N) to initial insect number (N_0) during thermal treatments was modeled as following the fundamental kinetic model:

$$\frac{d(N/N_0)}{\mathrm{d}t} = -k(N/N_0)^n, \tag{1}$$

where n is the kinetic order of reactions. The integration form of Eq. (1) was obtained for different reaction orders as follows:

$$\begin{aligned} \ln(N/N_0) &= -kt + c \quad (n = 1), \\ (N/N_0)^{1-n} &= -kt + c \quad (n \neq 1). \end{aligned} \tag{2}$$

A linear regression analysis was performed in this study for the 0-, 0.5th-, 1st, 1.5th- and 2nd-order of reactions. The best-fitted line was determined by comparing the coefficients of determination (R^2) for all the treated temperatures. After the reaction order was determined and the corresponding best-fit values of the constants k and c were obtained, the model was used to estimate the lethal time LT_{95}, LT_{99}, $\mathrm{LT}_{99.83}$, and $\mathrm{LT}_{99.9968}$.

The activation energy for thermal inactivation of test larvae was estimated from the relationship between k and T on an Arrhenius plot (Stumbo, 1973; Tang et al., 2000):

$$k = k_{ref}\mathrm{e}^{(-E_A/R)((1/T)-(1/T_{ref}))}, \tag{3}$$

where T is the absolute temperature (°K), k_{ref} is the reaction rate constant at the reference temperature T_{ref} (°K), E_A is the activation energy ($\mathrm{J\,mol^{-1}}$), and R is the universal gas constant ($8.314\,\mathrm{J\,mol^{-1}\,{}^{\circ}K^{-1}}$).

The activation energy E_A for thermal kill of codling moths was also estimated from a TDT curve (Tang et al., 2000):

$$E_A = \frac{2.303RT_{\min}T_{\max}}{z}, \tag{4}$$

where $T_{\min}$ and $T_{\max}$ are the minimum and maximum temperatures (°K) of a test range, respectively. z is the degrees of temperature increase required to result in one log reduction in time on a TDT curve. The z value in the theory of Thermobacteriology is related to the value of rate constant and activation energy in the classical reaction kinetic theory.

Once the z value, or k and E_A values, for a target insect pest are determined, the accumulated temperature–time effect of a thermal treatment with a known temperature history on reduction of the organism can then be predicted with good accuracy (Tang et al., 2000). This method has been the basis for calculating the thermal processing times for commercial food thermal pasteurization and sterilization processes (Stumbo, 1973).

2.4. Cumulative effect of ramp period

Different heating rates resulted in different ramp periods to reach the same holding temperature. It is possible to estimate the cumulative effect (corrected holding time) due to the temperature ramp periods. For first order kinetics, we may use the following relationship to approximately determine the cumulative effect for any given temperature–time history (Tang et al., 2000), in terms of equivalent total LT M_{accum} (min) at a reference temperature, T_{ref} (°C):

$$M_{accum} = \int_0^t 10^{(T(t)-T_{ref})/z}\,\mathrm{d}t. \tag{5}$$

The temperature–time history $T(t)$ for the treatments used in this study is presented in Fig. 1, where T_0 is the starting temperature (°C); T_h is the holding temperature (°C); t_0 and t_1 are the times (min) at the end of the ramp and the holding period, respectively. During the ramp period, the temperature is a linear function of time, and can be expressed as $T(t) = T_0 + \alpha t$, where α is the heating rate (°C min^{-1}). With this relationship and using the holding temperature as the reference temperature ($T_{ref} = T_h$), Eq. (5) can be directly integrated between the limits $t = 0$ and $t = t_1$ into:

$$M_{accum} = \frac{z}{2.303\alpha}\left[1 - 10^{-(T_0-T_h)/z}\right] + (t_1 - t_0), \tag{6}$$

where the first term represents the equivalent LT at the holding temperature accumulated during the ramp period, and the second term corresponds to the actual holding time. The above relation can be used to compare treatments at different heating rates, holding times and temperatures (Tang et al., 2000). An average z value of 4°C was used, based on the results of Ikediala et al.

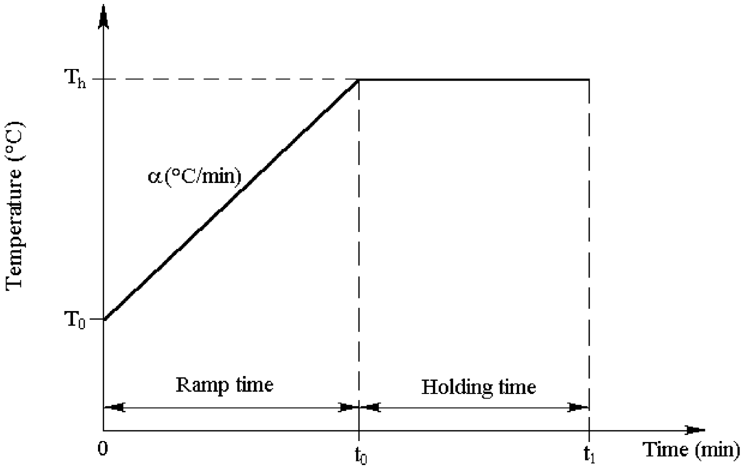

Fig. 1. Typical temperature–time history used in this study.

(2000), and the initial temperature was 22°C. The corrected treatment times corresponding to the three heating rates for the holding temperatures of 46°C, 48°C, 50°C, and 52°C were compared.

3. Results and discussion

3.1. Kinetics of codling moth mortality

The survival in unheated controls was high (92.4 ± 2.8%), suggesting negligible effect of shipping and handling. Table 1 gives the coefficients of determination (R^2) for different reaction orders for all the treatment temperatures to kill the codling moth larvae. The first order reaction was best suited to describe thermal mortality kinetics for fifth-instar codling moths at treatment temperatures above 48°C. But for the overall tested temperature range between 46°C and 52°C, the 0.5th order reaction was most applicable. The 0.5th order reaction was also found most suitable for fifth-instar navel orangeworms (Wang et al., 2002).

The thermal mortality curves for fifth-instar codling moths are shown in Fig. 2 together with the best-fit curves based on the 0.5th order reaction. The thermal death constants for the 0.5th-order reaction model are presented in Table 2. The established thermal death kinetic model was further used to predict the LT to reach 95%, 99%, 99.83%, and 99.9968% mortality (Table 3). Table 3 also lists the observed minimum holding times at each temperature to achieve 100% mortality in tested samples. Complete kill in samples of 600 insects was obtained after holding at 46, 48, 50, and 52°C for 50, 15, 5, and 2 min, respectively. The predicted values for $LT_{99.83}$ and $LT_{99.9968}$ were close to the observed results with samples of 600 insects. The discrepancy might have been caused by the limited resolution due to experimental holding time intervals (e.g., 0.5 to 1 min at 52°C but 10 to 15 min at 46°C) used in experiments at each holding temperature (Fig. 2). As expected, percentage mortality increased with increasing temperature and holding time. It is interesting to note in Table 3 that only about 10% extra time was needed to increase the efficacy of a heat treatment from 99% mortality to 99.9968% (Probit 9) when fifth-instar codling moths were fully exposed to a constant temperature.

Fig. 3 shows a TDT curve at the heating rate of 18°C min^{-1} that defines the minimum temperature and time requirements with the selected time intervals to achieve 100% kill of samples of 600 insects. The z value was estimated to be 4.2°C from the TDT curve. The observed

Table 1
Estimation of the best kinetic order (n) for the thermal kill of fifth-instar codling moths at four temperatures by comparing the coefficients of determination (R^2)

Temperatures (°C)	R^2 for different order n				
	$n = 0$	$n = 0.5$	$n = 1$	$n = 1.5$	$n = 2$
46	0.991	0.954	0.663	0.479	0.460
48	0.868	0.965	0.885	0.492	0.412
50	0.735	0.857	0.972	0.876	0.858
52	0.819	0.957	0.940	0.789	0.769

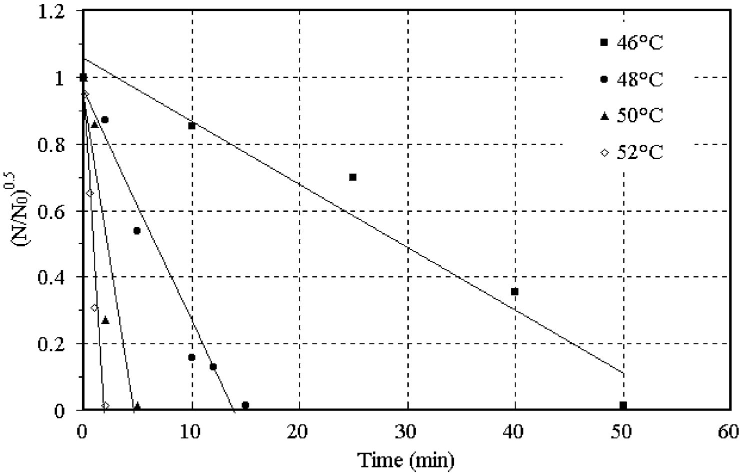

Fig. 2. Thermal mortality curve of fifth-instar codling moths at different temperatures and at the heating rate of 18°C min^{-1}. Each point represents 600 larvae and the lines were obtained by regression using a 0.5th order reaction model. N_0 and N stand for initial and survival insect numbers.

Table 2

Thermal death constants for 0.5th order reaction model for fifth-instar codling moth at four temperatures and the heating rate of 18°C min^{-1}

Temperature (°C)	Thermal death constants of $(N/N_0)^{0.5} = -kt + c$	
	$k \pm$ SE	$c \pm$ SE
46	0.0189 ± 0.0024	1.0555 ± 0.0984
48	0.0691 ± 0.0066	0.9584 ± 0.0869
50	0.2016 ± 0.0581	0.9401 ± 0.2175
52	0.5056 ± 0.0620	0.9488 ± 0.1013

Table 3

Comparison of lethal times (LT, min) obtained by experiments and 0.5th order kinetic models (Eq. (2)) for fifth-instar codling moths at four temperatures and the heating rate of 18°C min^{-1}, followed by 24 h cold storage at 4°C

Temperature (°C)	Observed 100% mortality for 600 insects (min) (~ $LT_{99.83}$)	0.5th order kinetic model			
		LT_{95}	LT_{99}	$LT_{99.83}$	$LT_{99.9968}$ (probit 9)
46	50	44.0	50.6	53.7	55.6
48	15	10.6	12.4	13.3	13.8
50	5	3.6	4.2	4.5	4.6
52	2	1.4	1.7	1.8	1.9

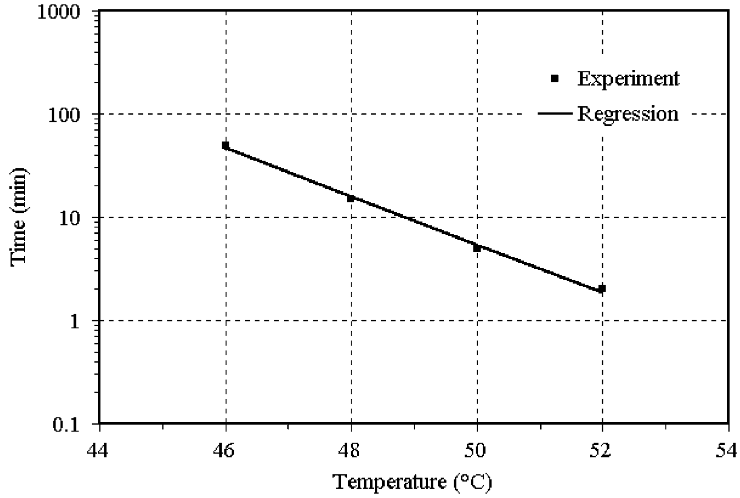

Fig. 3. Thermal-death-time curve defines minimum temperature-time to completely kill 600 fifth-instar codling moths at a heating rate of 18°C min^{-1}. The straight line ($\log t = 12.41 - 0.23T$) was obtained by linear regression ($R^2 = 0.996$).

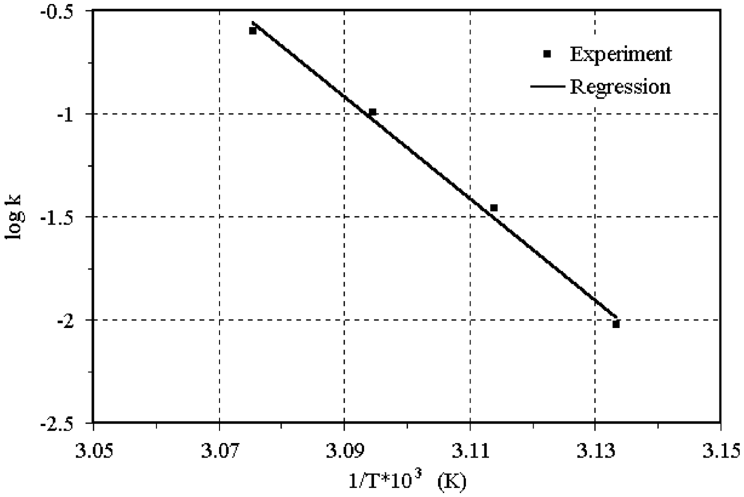

Fig. 4. Arrhenius plot for temperature effects on thermal death rates of fifth-instar codling moths. The straight line ($\log k = 75.22 - 24.64\times1000/T$) was obtained by linear regression ($R^2 = 0.995$).

exposure time for 100% mortality of all 600 test insects corresponded to the estimated LT needed to achieve at least 99.83% mortality at a given temperature. The relationship ($\log t = 12.41 - 0.23T$) between the observed exposure times to achieve 100% insect mortality and the treated temperatures was obtained by linear regression with $R^2 = 0.996$. The value of k obtained from 0.5th order reaction relationship followed an Arrhenius relationship (Eq. (3)) which is expressed as $\log k = 75.22 - 24.64\times1000/T$ with $R^2 = 0.995$ (Fig. 4).

3.2. Activation energy

The activation energy for thermal kill of fifth-instar codling moth was calculated from Eqs. (3) and (4), based on a z value of 4.2°C, to be 472 and 473 kJ mol^{-1}, respectively. Table 4 compares the activation energy (E_A) of different insect pests, microorganisms, and quality parameters of food commodities. The activation energy for thermal kill of the insects ranged from 400 to 958 kJ mol^{-1}. The E_A values for fifth-instar codling moths obtained in this study compared well with those of fifth-instar navel orangeworm (Wang et al., 2002) and of the four species of fruit flies reported by Jang (1986, 1991) and Moss and Chan (1993). In general, the activation energy for thermal kill of insects was slightly greater than that for thermal inactivation of pathogenic microbial spores and much greater than for softening and many other quality changes in commodities due to heat (Table 4). Like other insects, codling moth larvae were much more sensitive to increase in treatment temperatures than most fruit quality aspects. This provides an opportunity for the possible development of relatively high-temperature/short-time thermal treatment processes that may kill insects while having minimal impact on product quality (Tang et al., 2000).

3.3. Effect of heating rates on insect mortality

Table 5 highlights the effect of three heating rates on insect mortality under four temperature-holding time combinations (46°C + 40 min, 48°C + 5 min, 50°C + 2 min, and 52°C + 1 min). Using

Table 4
Comparisons of activation energies for thermal kill of insects and microorganisms with that for food quality changes due to heat treatments

Insects/materials	Temperature range (°C)	Activation energy E_A (kJ mol^{-1})	Source
Mediterranean fruit fly			
Eggs	45–47	784	Jang (1986)
First instar	45–48	656	Jang (1986)
Melon fly			
Eggs	43–46	518	Jang (1986)
First instar	45–48	650	Jang (1986)
Oriental fruit fly			
Eggs	43–46	958	Jang (1986)
First, early and late third instar	43–48	209–401	Jang (1986, 1991)
Caribbean fruit fly (eggs)	37–42	440	Moss and Chan (1993)
	43–50	445	Moss and Chan (1993)
Queensland fruit fly (eggs)	42–48	538[a]	Waddell et al. (2000)
Navel orangeworm (fifth-instar)[b]	46–54	510–520	Wang et al. (2002)
Codling moth (fifth-instar)[b]	46–52	473	This study (from TDT)
	46–52	472	This study (from $k-T$)
Quality (texture–softening or firmness, color, flavor, etc.)	50–70	42–126	Lund (1977), Rao and Lund (1986)
Microorganisms (spores)	100–130	222–502	Lund (1977)

[a] Estimated by the authors from the reported data.

[b] Parameter obtained at 18°C min^{-1} heating rate.

Table 5
Mortality (%) of fifth-instar codling moths after heat treatments with three different heating rates from 22°C and holding for selected periods (three replicates), followed by 24 h cold storage at 4°C

Temperature + holding time (°C + min)	Mortality (%) at heating rates		
	$1^{\circ}\mathrm{C\,min^{-1}}$	$10^{\circ}\mathrm{C\,min^{-1}}$	$18^{\circ}\mathrm{C\,min^{-1}}$
46 + 40	100 (24)[a]	100 (2.4)	87.4 ± 8.6 (1.3)
48 + 5	100 (26)	91.3 ± 6.2 (2.6)	71.0 ± 9.2 (1.4)
50 + 2	100 (28)	97.3 ± 1.9 (2.8)	92.5 ± 0.2 (1.6)
52 + 1	100 (30)	100 (3.0)	90.5 ± 6.4 (1.7)

[a] Value in the parenthesis indicates the ramp time to reach the targeted temperature in min.

the heating rate of $1^{\circ}\mathrm{C\,min^{-1}}$, all four treatments achieved 100% kill, whereas none of the four treatments achieved 100% kill when using the heating rate of $18^{\circ}\mathrm{C\,min^{-1}}$ (Table 5). The added thermal mortality in the treatment using slow heating rates, however, may be the result of the extended ramp period in which the insects were exposed to the elevated temperature. For example, the ramp time from 22°C to reach 52°C was 30 min when heating at $1^{\circ}\mathrm{C\,min^{-1}}$ compared to 1.7 min when heating at $18^{\circ}\mathrm{C\,min^{-1}}$.

The accumulated LT during ramp periods (M_{accum}) for the three heating rates from initial 22°C to the set temperatures was calculated using Eq. (5). The LT accumulated during the ramp period was about 1.8, 0.2, and 0.1 min (equivalent to holding time at the end temperature) for the heating rates of $1^{\circ}\mathrm{C\,min^{-1}}$, $10^{\circ}\mathrm{C\,min^{-1}}$, and $18^{\circ}\mathrm{C\,min^{-1}}$, respectively. Those values were not affected by the end temperatures. Adding the actual holding time listed in Table 5 to the accumulated LT during the ramp period suggested that the corrected treatment times at each temperature increased with the reduction in the heating rates. The accumulated LT had a significant effect on the short holding time at high temperatures. The incomplete kill of all four treatments at $18^{\circ}\mathrm{C\,min^{-1}}$ heating rate might be due to little lethality accumulated during the ramp period at the $18^{\circ}\mathrm{C\,min^{-1}}$. The large difference in the mortality (Table 5) between $10^{\circ}\mathrm{C\,min^{-1}}$ and $18^{\circ}\mathrm{C\,min^{-1}}$ may not have been caused by the small difference in the calculated cumulative LT. Explanation for the discrepancy requires further investigation.

This analysis has shown that treatments in which different heating rates were used to achieve the same holding temperature were not equivalent, and thus did not impart the same heat lethality. With slow heating rates, the insects would have been exposed to the lethal temperatures for a longer time than with treatments using faster rates. The contribution of the ramp period can be very significant at high temperatures if the heating rate is small.

Neven (1998a) observed that at heating rates between $0.13^{\circ}\mathrm{C\,min^{-1}}$ and $0.2^{\circ}\mathrm{C\,min^{-1}}$, the slower the rate of heating, the longer the codling moth larvae had to be exposed to the final treatment temperature to achieve 95% mortality. Lester and Greenwood (1997) also reported that a low heating rate and long exposure of insects to elevated but non-lethal temperatures ($<42^{\circ}$C) may condition insects such that subsequent treatment at lethal temperatures above 42°C are less effective. This implies that higher heating rate should provide greater mortality (require smaller

LT) because of a lack of non-lethal temperature conditioning of the insects. In this study, the total accumulated lethality required for 100% kill of the larvae appeared to be slightly higher at 1°C min^{-1} than at 18°C min^{-1}. This is contrary to what was observed by Neven (1998a). It is clear that the heating rates used in this study were much greater than those used by the above author and that the relatively long ramp time at even the lowest heating rate (1°C min^{-1}) tested in this study might not be adequate to allow insects to develop thermotolerance.

4. Conclusions

The heating block system was suitable for determining experimental data concerning temperature and heating rate effects on insect susceptibility to heat. Complete kill of 600 insects was achieved at a heating rate of 18°C min^{-1} with a minimum exposure time of 50, 15, 5, and 2 min at 46°C, 48°C, 50°C, and 52°C, respectively. The fundamental 0.5th reaction model was suited for predicting the thermal death kinetics of codling moth larvae. The activation energy for thermal kill of fifth-instar codling moth was about 473 kJ mol^{-1} both from a TDT curve and an Arrhenius plot. The LT accumulated during the ramp period to the end-point temperature was about 1.8, 0.2, and 0.1 min for the heating rates of 1°C min^{-1}, 10°C min^{-1}, and 18°C min^{-1}, respectively. The faster heating rate tended to require a longer holding time at the end temperatures to achieve similar mortality of codling moth larvae compared to the slower rate with test heating range. Fifth-instar codling moths were not able to increase their thermal tolerance with a decrease in the heating rate in the tested range. The methods and concepts described in this report may be extended to study other infesting pests of commodities for which heat treatment is being considered as an alternative quarantine treatment.

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